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APPLICATION FOR U.S. LETTERS PATENT

Title:

A digital Instantaneous Direction Finding system

In filing this non-provisional application, I claim the benefit of the filing date of Provisional Application Number 60/421,855 which I filed on 29 October 2002 and which bears the same title (under 35 U.S.C. § 119(e))

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Field of the invention

This invention generally relates to passive direction finding antenna systems for radio waves, and in particularly to antenna arrays that continuously observe over 360 degree arc in space, to determine the spatial direction of an incoming wave, and produce a digital output code, representing the direction of the incoming wave.

Description of the prior art

Many prior art methods of detecting the spatial direction of incoming radio signals are used, utilizing rotating focused antenna beams, as well as circular antenna arrays and direction finding receivers. Bumham and Clark, describe a direction finding system wherein the system employs a circular antenna array energizing a phase shifting network that produces output signals whose time phase is directly proportional to a spatial angle of an incoming RF signal. Thus for each different spatial angle of an incoming RF signal the system produces a different time phase angle, which is sampled and digitized to produce a digital output.

Background of the invention

In the simplest form of an antenna array used for direction finding, two antennas are used, as shown in figure 1. The RF signal phase delay, between antenna 1, and antenna 2, is:

$\Delta\phi = \frac{2\pi f}{C} A \sin\theta$, wherein $\Delta\phi$ is the phase difference between the antennas, f is the RF signal frequency, C is the speed of light, A is the distance between the antennas, and θ is the angle of arrival of the RF signal. In this equation, A and C are constant, f and $\Delta\phi$ must be measured, and θ is the unknown which the system needs to find. From the equation above, it results that

$$\theta = \arcsin\frac{(\Delta\phi)C}{2\pi f A} = \arcsin\frac{(\Delta\phi)}{2\pi} \times \frac{C}{Af}.$$

This invention describes a novel method of measuring the parameters f and $\Delta\phi$, in order to calculate the angle of arrival θ.

An array of two antennas can measure angle of arrival (azimuth) with respect to the axis perpendicular to the common axis connecting the two antennas. In a case shown in figure 2, the source of the RF signal may be on either side of the common axis line connecting the two antennas. The array of two antennas, as shown in figure 2, is unable to determine which side of the axis line a signal source is located. This problem is solved, by placing two more antennas, on an axis Q perpendicular to the axis I of the first two antennas, as shown in figure 3. The array of four antennas divides the horizontal plane to four quadrons, and thus an emitter can be located to one quadron and eliminate the ambiguity associated with the array of only two antennas.

The array of four antennas is viewed as comprised of two pairs of antennas. One pair is located on a horizontal axis named the *"I"* axis, and the other pair is located on the vertical axis named the *"Q"* axis. Each pair of antennas can determine the azimuth of an RF signal on all 360° around it, but with ambiguity with regards to which side of the axis connecting the two antennas the RF signal source is located. But since each pair of antennas is placed on an axis perpendicular to the axis of the other pair of antennas, the combined four antennas can determine the location of the RF signal source to a quadroon. Within every quadron, the azimuth measurement can be achieved using either pair of antennas, on either axis. However, since the phase difference $\Delta\phi$, is directly proportional to $\sin\theta$, the best angular resolution is obtained when $|\theta| < 45°$. To obtain the best azimuth measurement, the measurement on either axis is limited to an azimuth between $+45°$, and $-45°$. When $|\theta| > 45°$, the azimuth data is obtained from the pair of antennas on the alternate axis, as shown in figure 3.

The measurement of the angle of arrival of RF signals is not limited to the azimuth in the horizontal plane. The vertical angle, or elevation, of a source of RF signal can be measured in the same way horizontal azimuths are measured. Here an ambiguity exist, with regards to the location of the RF source, above, or below the horizontal plane on which the array of antennas is located. An additional antenna placed on a vertical axis Z, above one of the four other antennas, as shown in figures 4, and 5, eliminates the ambiguity, and enables measuring azimuth and elevation both in the hemisphere above the horizontal plane of the antennas, and the hemisphere below.

Prior art direction finding methods are not based on the direct measurement of phases. In most applications the phase is measure by means summations of analog RF signals, or the ratios between such RF signals. In alternative methods the RF signals are sampled and digitized, and Digital Signal Processing (DSP) methods involving complex arithmetic operations are used in order to calculate the desired phase. In this invention a new electronic circuit is used, which directly measures phase and frequency of RF signals without the elaborate calculations.

In this invention each antenna is connected to a receiver, and the output of each receiver is connected to a phase digitizer. The phase digitizer is a device with a digital output indicating the instantaneous phase of the RF signal at its input, at the instance of the instruction clock transition. The clock is typically a periodical signal at a high frequency, and the phase digitizer outputs a new word of data on every clock cycle. The same clock is delivered to all the phase digitizers in the system, such that the transition time will be exactly the same on all the digitizers. This guarantees that when a signal arrives at every antenna at exactly the same phase, all the phase digitizers will indicate the same phase, ϕ, on the same clock transition time. The value $\Delta\phi$, is calculated simply by subtracting the phase data on one digitizer, from that of the second digitizer receiving signals from the second antenna in the pair of antennas. The result is $\Delta\phi = \phi_1 - \phi_2$, wherein ϕ_1 is the output of the phase digitizer receiving signals from antenna 1, and ϕ_2 is the output of the second phase digitizer, receiving signals from antenna 2 in the pair of antennas.

The other parameter necessary to calculate the angle of arrival is the frequency of the arriving signal. By definition, the frequency of the signal is the rate of change of it phase over a period of time, $f = \frac{d\phi}{dt}$. The output of the phase digitizer is the instantaneous phase ϕ_k, and the clock period is t_c. Therefore, the instantaneous frequency of the incoming RF signal is $F = \frac{\phi_k - \phi_{k+1}}{t_c}$, wherein ϕ_k, is the instantaneous phase at time k, and ϕ_{k+1}, is the instantaneous phase one clock period later, at the time k+1.

To increase the accuracy of all the measurements, both $\Delta\phi$, and F are averaged over a number (n) consecutive clock periods.

To guarantee the best angle resolution, it was determined that each pair of antennas will only be used in measuring angles between $+45°$, and $-45°$, Or, $|\theta| < 45°$. Digital magnitude comparators are used to compare the phase differences measured between antennas on the different axes (I,Q, or Z), and determine which axis is used for the final measurement output.

The range of frequencies for which the direction finding system can provide a correct azimuth or elevation information is limited by a couple of conditions. The first limiting factor is the distance between the two antennas on an axis. If this distance is greater than the wavelength of the incoming RF signal, the system is unable to determine the exact phase difference between the antennas. A second limitation depends on the frequency of the sampling clock. The Nyquist rule

requires that the clock frequency is more the twice the highest frequency sampled, or for that matter, the frequency bandwidth, in the phase digitizer input. Combined, the distance between the antennas, and the clock frequency determine the operational limits of the system.

In some other applications for finding the direction of an emitter of radio signals, two directional antennas are used. Directional antennas exhibit a large gain for signals received in the forward direction of the antenna, and a large attenuation for signals coming from other directions, especially from the direction opposite to the antenna's forward direction. Such antennas include YAGI, and dish type antennas.

When an array of two directional antennas are used, wherein both antennas are facing the same direction, a direction finding system, to find the azimuth to a source of radio signals, within a semicircle of 180°, can be built. Since the antennas are highly directional, the direction finding system based on such antennas does not suffer the problem of ambiguity, as is the case with omnidirectional antennas typically used in other types of direction finding systems. A typical application for such direction finding system is in airplanes wherein an array of two directional antennas on the wings is used to construct a forward looking direction finding system.

Beside instantaneous direction finding, there are other applications, which can utilize the same phase difference measurement method in accordance with this invention. Two such applications are the "monopulse" radar system, and an electronic warfare system known as "cross eye", which is used to deceive the azimuth detection systems of hostile "monopulse" radars.

A "monopulse" type radar is comprised of two or more highly directional antennas, all aimed at the same direction, as shown in figure 13. In this type of a radar system, like in any radar, an impulse of RF signal is transmitted to a target, and the two antennas are used to detect the direction of a target by comparing the phase difference between the signals reflected from the target as they are received by the two antennas. The monopulse radar is aimed directly to the target when the phase of reflected signals is equal on both antennas. Monopulse radars are typically used in the military for fire control, wherein these radars control the direction of fire towards the target.

The "cross eye" electronic warfare system shown in figure 14, is used on "target" airplanes to deceive hostile monopulse radars, by obstructing the direction finding capabilities of the monopulse radar, and preventing it from aiming directly at a target. In the "cross eye" system, radar signals are received by two forward-looking antennas, each mounted on one tip of the aircraft wings. The received signals are digitized and stored in a temporary memory.

Subsequently the stored signals are recalled and retransmitted through the two antennas such the phase of the transmitted signals on either antenna is varied, resulting in two simultaneous signals being transmitted, which are identical in all their parameters except for their phase. The monopulse radar receiving the two signals of different phases is unable to determine the true direction from which these signals come, and thus is deceived and deprived of its direction finding capabilities.

Description of the drawings

Figure 1, Shows the phase relationship in an array of two antennas.

Figure 2, Shows a case where RF emitter may be located on either sides of an antenna array.

Figure 3, Shows an array of four antennas comprised of two arrays in quadrature.

Figure 4, Shows an array of 5 antennas, for azimuth and elevation detection.

Figure 5, Shows the phase relationship, and method for measurement of elevation angle.

Figure 6, Shows an embodiment of the azimuth and elevation detection system.

Figure 7, Shows an embodiment of a typical RF receiver.

Figure 8, Shows a block diagram of a phase digitizer.

Figure 9, Shows an embodiment of the quantizer section of the phase digitizer.

Figure 10, Shows the waveforms at the outputs of the comparators.

Figure 11, Shows the Linear to Grey code conversion.

Figure 12, Shows the Grey code to Binary code conversion.

Figure 13, Shows signals and phases in a "monopulse" type radar.

Figure 14, Shows a block diagram of a "cross-eye" system.

Description of the invention

To better understand the description of this invention, refer to figure 6, 7, and 8. Figure 6 shows an embodiment of the system capable of determining the azimuth and elevation of an emitter of RF signal. As shown, 5 antennas are used, each connected to a radio frequency receiver. An embodiment of a typical RF receiver is shown in figure 7. The signal received by the antenna (100), is aplified by the high gain amplifier (101) to the point where the output of the amplifier (103) is limited to the form of a square wave, and then filtered by a bandpass filter (102). The frequency domain spectrum of the square wave is comprised of fundamental frequency an infinite number of odd harmonics of that frequency. The bandpass filter (102) removes all the harmonics allowing only the fundamental frequency to pass through. Comprised of only a single spectral line, the output of the filter (102) is a pure sinewave. The bandpass filter (102) is followed by another linear amplification stage (103) to compensate for losses in the filter (102) and to bring the amplitude of the amplified sinewave to a predetermined magnitude. The output of the second amplification stage (103) connects to a power splitter (104) which splits the signal at the output of the amplifier (103) into two identical signals, similar to the signal at the output of the amplifier (103) but with half the power for each signal. Of the divided signals, one half (111) connects to a RF mixer (105), and the other signal (112), connects to the RF mixer (106).

Each of the mixers (105, 106) has three ports, an input (RF) port, a local oscillator (LO) port, and an output (IF) port. The function of the mixers is to multiply the signal on its input port with the signal on its LO port, to generate an output signal combined of two frequencies, one frequency equals the frequency difference between the frequencies of the RF and the LO inputs to the mixer, while the other output frequency equals the sum of the frequencies of the mixer's two inputs. The LO input ports of the mixers are connected to the hybrid coupler (107) through which they receive signals that generated generated by the local oscillator (108). The local oscillator (108) generates a signal at a high frequency, such that when this signal frequency is subtracted from the frequency of the signal at the outputs of the splitter (104), it will produce an output (IF) signal from the mixers, at a frequency smaller than half the sampling clock frequency (55). The output of the local oscillator (108) is connected to the input of a hybrid coupler (107). The hybrid coupler is similar in it function to that of a power splitter, in dividing the power of a signal at its input between two outputs with half the power at each output. The hybrid coupler differs from the power splitter (104) in having the phase of one of its outputs shifted by 90° with respect to phase of the other output. The outputs (113, 114) of the hybrid coupler (107) are connected to the LO ports of the mixers (105, 106), respectively. The mixers receiving input signals (113, 114) on

their LO inputs that are phase shifted by 90° from each other, poduce each a low frequency output that is also phased by 90° with respect to the output signal phase of the other mixer. This condition is otherwise known in the trade of RF and microwave as a quadrature condition. The output of each mixer (105, or 106) is connected to a lowpass filter (109, or 110) respectively. The lowpass filters are selected such that they attenuate and eliminate any signal at a frequency higher than half the system sampling clock (55) frequency. The outputs (115, 116) of these lowpass filters (109, 110) are the baseband signals applied to the phase digitizer.

Figure 8, shows a block diagram of a phase digitizer. As shown, the digitizer is comprised of two blocks, the quantizing block (50), and the code conversion block (51).

An embodiment of the quantizer block is shown in figure 9. The quantizer recieves two pure sinewave inputs, an I input (115), and a Q input (116), which are identical copies of each other, but are in quadrature to each other, meaning they are phase shifted by 90° from each other. These two inputs feed a network of resistors (52). The resistor network (52) combine different ratios of the signals from the inputs (115, 116), performing a vectorial summation between different magnitudes od quadrature sinewaves to produce n sinewaves (57), all of the same frequency, but phase shifted from one to another by $\Delta\Psi = \frac{\Pi}{n}$ radians. The n sinewaves (57) generated by the resistor network (52) are applied to the inputs on n comparators (53), which in turn generate n streams of phase (time) shifted squarewaves (56), which are applied to the D inputs of n master-slave type flip-flops (54). Figure 10, shows the waveforms (56) at the outputs of the comparators. The flip-flops (54) capture the waveforms generated by the comparators (53), on the transition of the clock (55), and each flip-flop (k) provides two complementary outputs (58), P_k, and $P_k\backslash$, which represent the sampled signal phase in a linear code fasion. For every phase of the signal at the inputs (115, 116) of the quantizer, there a different combination of logic states in the output bits (58) of the quantizer. In order to be useful in digital calculations the linear code of the quantizer output bits (58) need to be converted to a binary code.

The conversion of the linear code to a binary code according to this invention and as shown in the embodiment described here, is performed using simle logic elements in a two steps process. In the first step, the linear code is translated into a Grey code using Exclusive OR functions as demonstrated in figure 11 by an example for a digitizer where n=16. The conversion of 16 signals into a 4 bits GRAY code follows as: $G0 = P1 \oplus P3 \oplus P5 \oplus P7$, $G1 = P2 \oplus P6$, $G2 = P0$, and $G3 = P4$, wherein *G0, G1, G2,* and *G3* are the Grey code bits. The second step of conversion is demonstrated in figure 12, and also utilizes EXOR functions, to convert the Grey code to a Binary code, as follows: $B0 = G0 \oplus G1 \oplus G2 \oplus G3$, $B1 = G1 \oplus G2 \oplus G3$,

$B2 = G2 \oplus G3$, and $B3 = G3$. The Binary code bits are *B0, B1, B2,* and *B3,* and they provide a numerical value of the phase of the signal at the input to the digitizer at the instance of the sampling clock (55) transition.

Figure 6 shows an embodiment of the digital azimuth and elevation angle detection system. In this system 5 antennas are employed. Two antennas for the I axis, two antennas for the Q axis, and an additional antenna for the Z axis. Each antenna connects to a receiver similar to the one shown in figure 7. Receivers (1) and (2) connect to the antennas of the I axis. Receivers (3) and (4) connect to the antennas of the Q axis, and receiver (16) connect to the Z axis antenna. Each receiver provides two quadrature outputs (115, 116), which are connected to corresponding phase digitizers. Phase digitizers (5) and (6) receive the quadrature outputs of the receivers (1) and (2). Likewise phase digitizers (7) and (8) receive the quadrature outputs of the receivers (3) and (4), and the phase digitizer (17) connects to the output of the receiver (16). The outputs of the digitizers, each provides a numerical value of the phase of the signal at the input to the corresponding digitizer at the instance of the sampling clock (55) transition. These five instantaneous phases are used to calculate the azimuth and elevation angles.

One parameter essential to these calculations is the frequency of the received signal. The frequency of a signal is defined as the rate of change of its phase over time, $f = \frac{d\phi}{dt}$. In the digital system the instantaneous phase value is a discrete digital value, at the instance of the clock transition. The frequency is thus the phase difference over a period of time, and the instantaneous frequency is the difference between the instantaneous phases of any two consecutive samples, divided by the sampling clock period time. $F = \frac{\phi_k - \phi_{k+1}}{t_c}$, wherein ϕ_k, is the instantaneous phase at sampling time k, and ϕ_{k+1}, is the instantaneous phase one clock period later, at the sampling time k+1. The task of measuring the instantaneous frequency is performed using the register (9) and the subtractor (10). Instantaneous phase of the received signal, in a digital form, is generated by a digitizer (5). This digital data ϕ_k is supplies both to the register (9) and to B input of the subtractor (10). The digital data ϕ_k is delayed one clock period by the register (9), and therefore this digital data appears at the A input of the subtractor (10) one clock period later, while at the B input of the subtractor (10) a new digital data ϕ_{k+1} already appears. Thus the subtractor (10) performing the function A-B in fact calculate $\phi_k . \phi_{k+1}$. Since the time period of the sampling clock t_c is known so is the instantaneous frequency $F = \frac{\phi_k - \phi_{k+1}}{t_c}$.

To improve the precision of the frequency measurement, the output (21) of the subtractor (10) is applied to an averager (11), which calculates the running average value of the frequency measured over a period of v clock cycles.

To measure the azimuth, phase differences are measured on two axis, the I axis and the Q axis. The phase difference on the I axis is measured using the subtractor (12) which subtracts the instantaneous phase data (58) generated by phase digitizer (6) from the instantaneous phase data generated by the phase digitizer (5). Thus the output (23) of the subtractor (12) is the phase difference between the phase measured by the digitizer (5) and the phase measure by the digitizer (6). To obtain a higher precision in phase difference measurement, the output (23) of the subtractor (12) is applied to a running averager (13), which calculates the average phase difference over a period of u clock cycles. Similarly the phase difference on the Q axis is measured using the subtractor (14), which subtracts the instantaneous phase data (58) generated by phase digitizer (8) from the instantaneous phase data generated by the phase digitizer (7). the output (25) of the subtractor (14) is the phase difference between the phase measured by the digitizer (7) and the phase measure by the digitizer (8). To obtain a higher precision in phase difference measurement, the output (25) of the subtractor (14) is applied to a running averager (15), which calculates the average phase difference over a period of u clock cycles. Using the phase difference output (24) of the averager (13), the phase difference output (26) of the averager (15), and the frequency output (22) generated by the averager (11), the azimuth is calculated as: $\theta = \arcsin \frac{(\Delta\phi)}{2\pi} \times \frac{C}{Af} = \arcsin \frac{C}{2\pi A} \times \frac{(\Delta\phi)}{f}$, wherein C is the speed of light, and A is the distance between the two antennas on the axis. $(\Delta\phi)$ is the measure phase difference on an axis, and f is the measured signal frequency.

Elevation measuremant is similar to the azimuth measurment except that phase differnces are measured on the z axis instead of the I and Q axis. For this purpose the subtractor (18) calculates the phase difference between the instantaneous phase data output of the phase digitizer (8) and the instantaneous phase data output of the phase digitizer (17). The output (27) of the subtractor (18) is applied to the running averager (19). The output (28) of the averager (19) is a more accurate quantification of the elevation angle.